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A CRITICAL ANALYSIS OF THE PONT DE NORMANDIE CABLE-STAYED BRIDGE

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Abstract: This paper aims to develop a critical understanding of the design and construction of the Normandy Bridge. It will demonstrate an understanding of many aspects of bridge engineering whilst assessing what has been done appropriately and what has could have been improved upon with regards to the current use of the bridge. Some of the aspects into which this paper will look are the aesthetics of the bridge, the construction of the bridge, the materials used in the bridge, the loadings on the bridge, the strength of the bridge, the potential for any future changes to the bridge and the maintenance of the bridge. All of these factors are of absolute importance to the understanding and deconstruction of the workings of this bridge and the logic behind it.

Keywords: *bridge, cable-stayed, Normandy, steel, concrete*

1 Introduction

The Normandy Bridge was officially opened on the 20th of January 1995 as cited in Ref. [2] and at the time was the largest spanning cable-stayed bridge in the world with a longest span of 856m, over 250m greater than the previous greatest single span found in a cable-stayed bridge structure. The total span of the bridge is 2143.21m. It was designed by Michel Virlogeux, who would later go on to design the Millau Viaduct, and the architects were François Doyelle and Charles Lavigne. The bridge is situated in northern France and spans between Honfleur and Le Havre over the River Seine. The bridge rises to 52m above the highest water level in order not to impede the large cargo vessels that use the river. It was built to relieve the older Tancarville Bridge and to open up western France to traffic. The main live loadings will therefore be traffic loading, though in the location wind loading may also be critical. There was also purely the challenge of constructing the longest bridge of its kind in the world especially with the alluvial terrain with no natural anchorage points as cited in Ref. [7]. The immediate surrounding area to the bridge is fairly sparsely populated and is predominantly taken up by industrial estates sited on the banks of the river, while the part of the river being spanned is extremely close to the mouth of the river and the sea, hence there is such a long distance to be spanned. At the end of construction, the bridge ended up costing a total of $465 million.

2 Why choose a cable-stayed bridge?

There were several reasons for choosing to build a cable-stayed bridge here as opposed to a suspension bridge which is the other type of bridge that might have been used to cross such a large span. Firstly, it is cheaper to construct a cable-stayed bridge as the spinning of the main cables in a suspension bridge is very expensive and far more complicated to get exactly right in comparison with using many more, smaller, cables. The poor soil conditions in and around the river mouth area would not have been strong enough to take the massive anchorages required for a suspension bridge, therefore the main structural elements of the entire bridge are the two 20,000t, 214.77m tall, pre-stressed concrete pylons, and are the highest bridge towers of this type in the world as stated in Ref [3]. They need to be very, very stiff in order to allow for the relatively thin and flexible deck. Having the deck thin and flexible and the pylons massive and stiff requires many closely-spaced stays, and this bridge has 184 in total in a ‘semi-harp’ configuration where the stays are not completely parallel but rather they get closer together the nearer they get to the pylons. The most efficient pattern for the stays to be in is to have all stays converging at the very top of the pylon. The reasons for not doing this however are two-fold – firstly the issue of connecting a large number of stays to the top of each pylon is a very difficult one to deal with as there just physically is not enough room for all of the cables to connect to the pylon, and secondly it would be less aesthetically pleasing. The pylons are in an upside-down ‘Y’-shape with all of the stays connecting to the pylons in the straight ‘tail’ section of the pylon. There is a big advantage to having a pylon in this shape as opposed to having two vertical pylons, and this is that this system

increases the torsional stiffness of the bridge by having a closed section.

There is an argument that having a pylon design like this is more suited to a single plane of cables to achieve a more aesthetically pleasing effect without having the effect of cables crossing when viewing the bridge. This would not be highly practical for this bridge as the deck is relatively shallow and therefore does not have a very large cross section which would be necessary to take the torsional effects on the bridge as the single plane of cables would not be able to deal with this sufficiently. If this was desired in the bridge it would only lead to inefficient design as with all the closely spaced cables, the deck would only need to be slender to resist bending, but would need to be substantially stiffened to take the torsion. In aerodynamic analyses of wind loading, both at normal wind speeds and at storm wind speeds, the results in terms of deformations of a cable-stayed bridge with a 'Y'-shaped pylon, are much better than the results for the same wind loadings on a suspension bridge or a cable-stayed bridge which does not have a 'closed' section.

3 Aesthetics of the bridge

Famous bridge engineer Fritz Leonhardt used a set of 10 rules against which a bridge can be measured to decide whether the bridge is aesthetically pleasing or not and I will be analysing the bridge critically using these rules.

3.1 Fulfillment of function

Straightforwardly, the functionality of the bridge must be taken into account, and it should be predominantly to see whether everything in the structure is of some purpose and is not superfluous. Even from afar, it is very clear how the structure works, that the deck is supported by the cable-stays in the main span and that these are supported by the massive pylons, and that elsewhere the piers support the deck and raise it up to the required level above the water level. It is intuitively very clear what everything is doing structurally. In these respects I feel that the bridge succeeds totally in being functional.

3.2 Proportions of the bridge

The ratios of depths and spans should be so that quite simply the bridge looks in proportion. The deck must not seem too deep in relation to the size of the pylons and the piers. With the Normandy Bridge having extremely large pylons, and a relatively shallow deck, it can perhaps at first look slightly out of proportion, but upon closer inspection it seems to me that the thicknesses of the pylon and deck are not so dissimilar as to look totally out of proportion. The ratio of the main span compared to the spans between the piers may at first seem to be completely out of proportion, but due to the symmetry of the piers at either end of the bridge, this impression is successfully avoided. I feel that the dimensions of the bridge are suitable to make the entire structure seem very pleasing on the eye, and give the impression that the structure is actually quite lightweight.

3.3 Order within the structure

The relative narrowness of the cable stays compared with the depth of the deck or thickness of the pylon mean that from a distance they almost seem not to exist, though this is partly down to the colour which will be referred to later on. The issue of order is that when there is poor order in a bridge it can make it quite difficult to look at and span from one end to the other, with the span being disrupted by broken edges or crossing lines.

With a cable-stayed bridge such as this one the main issue to do with order is to do with the cables crossing and the strange effects this can have. However in the case of this bridge this is not an issue, the cables are in a configuration that mean that there is just a fan effect that one gets when scanning from left to right across the bridge. This is partly due to the 'semi-harp' layout of the cables and the fact that all of the cables converge to almost a single plane at the pylon. If the bridge had had a cable layout where all the cables were parallel, and if the pylons were two separate columns as opposed to 'Y'-frames, then there would be some issues of order as when the bridge was viewed from various angles as all of the cables would appear to cross and create obstacles. This is why I believe the bridge to possess very good order and is very successful, as it avoided these potential pitfalls. The only possible criticism is the use of the damping cables which cross the cable-stays almost perpendicularly, and create and obstacle when panning across the bridge, though this is only evident at fairly close quarters.

3.4 Refinement of Design

The refinement of the design is important to the aesthetics as is shows that the way the bridge will look when finished has been thought about and considered carefully at the design stage. It shows care has been taken over the appearance of the bridge. The way that the 'Y'-frame joins the two columns into one gives the impression of the pylon tapering and looking smaller at the top than at the bottom so there is no illogical illusion of the structure being larger at the top than at the bottom as can happen with parallel edged columns. The piers also have a very slight taper to them and are spaced far enough apart so as not to create an opaque barrier from oblique angles. Perhaps the only place where this bridge could have been more refined in its design is when getting nearer to the banks of the river at either end of the bridge, the piers could perhaps become closer together to maintain the aspect ratio between the ground, the piers and the deck.

3.5 Integration into the environment

Making sure that the bridge fits into the environment is very important as the bridge will fill a large part of the landscape in the area and will last for a very long time, thus it is extremely undesirable for it to look out of place in its surroundings. The Normandy Bridge is situated over a large expanse of water and is surrounded mostly by industrial estates and is sparsely populated. The materials of pre-stressed concrete and steel fit in with these surrounding buildings very well and match what is already there. The style of bridge also fits the environment perfectly; cable-stayed bridges are very suited to spanning large bodies of water and can look quite spectacular, especially on the scale of the Normandy Bridge. With the materials and style used here, the bridge is very successfully integrated into the environment.

3.6 Texture of the surfaces

This is probably one of the less crucial factors in judging the aesthetic qualities of a bridge as it will more or less only be important when very much up close to the structure. It is also potentially a factor when the materials being used are perhaps more uncommon than steel and concrete. The Normandy Bridge, with its vast concrete pylons and piers from afar will not appear to have much surface texture at all, and even up close there is not a great deal of texture. The concrete is deliberately smooth-surfaced with a matt finish so as to give crisp boundaries to the structure against its surroundings. A possible failing with regards to surface texture is that when using concrete, no matter how hard one tries it is going to be almost impossible to get two lots of concrete 100% identical so there may be a discrepancy in the colour and the texture of the concrete surfaces in the bridge.

3.7 Colour of bridge components

The intended effects of the use of colour in a bridge can be many-fold. Particular components can be highlighted to seemingly add extra significance to them. Alternatively elements can be 'hidden' by using colours similar to the background to the element so it seems to blend in with this background. As the Normandy Bridge is a predominantly concrete structure which already fits into its environment very well, there is no need to accentuate or hide any of the main structural elements, i.e. the pylons, piers and deck. What can, and has, been done is that the cables can be painted light colours in what gives a dual benefit to the bridge; firstly, painting the cables helps protect the steel in them from the elements and reduces the potential for corrosion due to rain and wind, and secondly by painting the cables a light colour, they become much less conspicuous. This gives the impression from afar that the deck is supported only by the two pylons with a spectacular and massive main span. Painting the cables a light colour also means that there is less likely to be an issue with the order of the bridge as any cables crossing will be less visible anyway. The deck has a blue streak running all along the side of it. This creates the illusion of the deck floating in the sky.

Another way to utilise colour is with the night time lighting on the bridge. The scheme on the Normandy Bridge is that the underside of the deck has lots of individual blue lights running all the way along the deck on either side to give the impression of the water reflecting onto the bottom of the bridge. There are also blue lights shining up from the base of each side of each pylon to continue the water effect all the way along the bridge. The only other lighting on the bridge is the street lamps above the deck. This gives a fantastic effect of the traffic on the deck floating in between these two reams of light. The use of colour on this bridge has deliberately been subtle during the daytime use of the bridge and is rightly limited to making the cables appear more subtle, whereas the night time lighting is deliberately spectacular in order to show off the bridge and make it a landmark during the night. It is aesthetically pleasing whilst also being functional. Thus I feel the use of colour on this bridge has been very successful.

3.8 Character of the bridge

A bridge having character seems outwardly to be a fairly outlandish concept, which is very difficult to grasp or put a finger on as to exactly what it is. It is perhaps the 'wow' factor or the ability to make people question how it works and to make them think about the bridge. Whatever it is, for a bridge to be truly beautiful and aesthetically pleasing, it needs to possess character. I feel that the Normandy Bridge definitely possesses character. It is the way it rises up out of the banks of the river. It is the sheer scale of the structure that helps to give it its character; it is a monument in the area and is a stunning sight from a great distance. That the bridge uses a 'Y'-frame helps to give it character and makes it more distinctive from many other cable-stayed bridges which have two individual towers at each pylon. The cable-stayed design is at its most iconic across large spans of water such as in this situation so it stands out. I feel that these factors all contribute to the bridge having a lot of character.

3.9 Complexity in variety of the bridge

Too much complexity in the design of a bridge can lead to chaos when trying to view the bridge. There is therefore clearly a limit on the amount of complexity than can be in a design, as complexity can make a bridge visually stimulating so is desirable but at the same time it is desirable to stick to the edict of 'keep it simple'. With the Normandy Bridge there is a degree of complexity introduced by the cables in the structure. Overall, however, the design is fairly simple and straightforward, with the hierarchy of how things work being clear just from looking at the bridge; the deck is supported by the piers and the cables, and the cables are anchored into, and supported by the pylons and that the pylons anchor the entire structure. At the same time, the bridge has enough complexity to grab somebody's attention and make the bridge interesting viewing. The fact that the bridge rises and falls so much across its span gives the bridge much of its shape, and this is adding to the complexity without introducing any form of chaos into the design. The closest the bridge comes to any form of chaos is where the cable stays get closer together near the pylon, but even this is not hugely noticeable. The Normandy Bridge is complex enough to visually stimulate, but not so complex as to cause a sense of disorder when viewing it.

3.10 Incorporation of nature

Incorporating nature into the design of structures makes sense in that natural structural systems have evolved over millions of years into the most efficient systems possible. Therefore copying these forms and using them to the benefit of man is a sensible thing to attempt. In relation to this bridge, however, there is little incorporation of natural forms, nor is there any great attempt to incorporate the bridge into the nature of the surroundings, although most of the surroundings are industrial estates so there is not much nature in or around the site to fit in with. One similarity to natural structures could be argued to be between the cable-stays and a spider web. The spider web is of course a totally cable-based structure whereas only part of the bridge structure uses cables. This shows how nature has influenced many structures with the use of cables for example. During the design of the Normandy Bridge it was probably not consciously thought about as being influenced by nature.

I would say that the bridge does not incorporate nature hugely but as a qualifier that it is also difficult to see how any natural structural forms could be incorporated into the cable-stayed bridge design.

3.11 Evaluation of the bridge aesthetics

Having looked at the bridge against all of the ten rules as laid out by Fritz Leonhardt, I feel that the Normandy Bridge can be said to be a very aesthetically pleasing bridge, perhaps even beautiful. It is successful or very successful with respect to eight of the rules.

The rules where it perhaps was not so successful were on the incorporation of nature and the textures of the surfaces. These, I feel for this bridge, it the location it is in, are less important than the other rules. The reason I feel that it does not matter that it fails to incorporate nature massively is that the surrounding area is industrial estates, so effectively the nature into which it is being built is one where all the surroundings are unnatural in the classic sense of the word. It means that the bridge, a vast mass of concrete and steel, fits in where it is. The fact that the textures are uninteresting also is less important than other things I feel because being a predominantly concrete structure, there is fairly limited scope for being creative with surface textures, especially due to the scale of the bridge in question.

In conclusion I feel that the Normandy Bridge meets enough of the criteria very strongly to be considered a very attractive bridge indeed.

4 Construction and materials of the bridge

The construction of the Normandy Bridge lasted from 1988 to 1994, and the site was the largest construction site in the whole of France during this time. I will discuss the construction of each element of the bridge individually.

4.1 Pylons

The two pylons are identical except that the north pylon is built in the river channel whereas the south pylon is built on the bank of the river. This meant that extra protection was required around the foundations of this pylon as shown in Fig. 1:

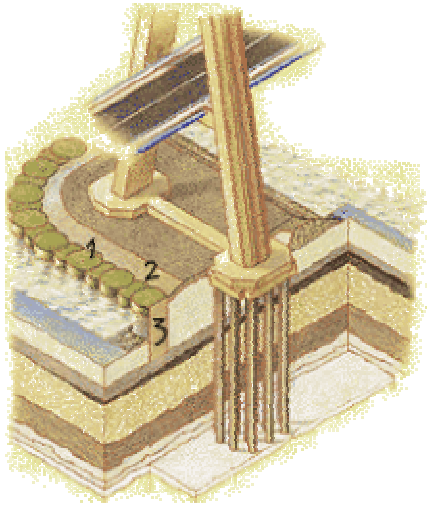

Figure 1: Extra protection for north pylon foundation taken from Ref. [4].

The extra protection for the foundation consisted of thirteen circular cofferdams with a diameter of 8.92m, twelve connection cofferdams, all of which were raised to 16m above the riverbed. The cofferdams create a dry area in which construction can take place which greatly improves potential working conditions for the construction of foundations. This gave the most suitable and stable area in which to sink the pile foundations for the pylons. In total there are 56 piles, each with a diameter of 2.1m. There are 14 piles beneath each of the four pylon 'feet', and each of these piles was sunk to a depth of 50.5m and each pile can resist a loading of 3,000t. Using a pile foundation is the only real solution to creating a suitable footing for such an enormous structure, especially when each pylon alone weighs 20,000t before the introduction of the deck, cables, dead and live loads. The pylons are required to be very, very stiff to the point where they cannot be allowed to move at all in order to allow for the shallow deck with many cable-stays.

The pylons are made from pre-stressed concrete, and I think due to the difficulties that would ensue trying to post-tension the concrete, that the concrete is pre-tensioned concrete where the concrete is cast around already tensioned tendons. This produces an excellent bond between the steel and concrete and means that there is a direct transfer of tension in the structure, as well as the concrete providing corrosion protection to the steel. The way the pylons were constructed was in relatively small layers that could have been cast on site, or could have been pre-cast. In this situation, I think it would have made less sense to use pre-cast concrete so as it would not be able to be utilized to create pre-tensioned concrete in one continuous structure. Casting in-situ would also have its benefits in that there would be no transport costs involved and also casting on site would make more sense with regards to creating pre-stressed concrete. The pre-stress in the steel in the pylons is 150t.

One of the most difficult problems with the pylons is how to successfully connect the 92 cable-stays. The heads of the pylons have steel caissons enclosed in the concrete, and these are what the cable-stays are anchored in to. This makes sense in that it would be almost impossible to successfully connect the cables to a monolithic concrete structure. The cables are connected as shown in Fig. 2:

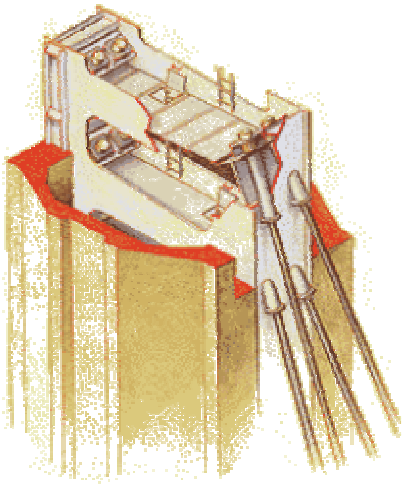

Figure 2: Connection of cables to pylon taken from Ref [4].

Having two sets of cables coming out of each side of each pylon gives a sense of symmetry and of balance to the whole structure. The whole bridge looks like two enormous sets of scales, perfectly balanced.

4.2 Cable-stays

The cables are split into eight groups of 23 to make up the total of 184 cables. The cables range in length from 95m at their shortest to 460m at their longest. Each cable is made up of a bundle of wires, with each wire being made up of seven strands of galvanized steel. There are three cable-stay make-ups; there are 31, 44 or 53 strands in the cable. The cables are clad in a polyethylene sheath and then a petroleum-based wax is used to fill in the spaces between the wires and the sheath of the cable (see Fig. 3) as stated in Ref. [3]. This is all done in order to protect the key structural elements of the bridge, as if the cables are exposed to the elements and are allowed to corrode, then this could seriously undermine the structural stability of the entire bridge. The theoretical breaking load of each strand is 27t, though the tension in service is just 10t, therefore there is clearly a large safety factor built in. This is of course standard, but evidently a very sensible thing to do with such an important element of the bridge.

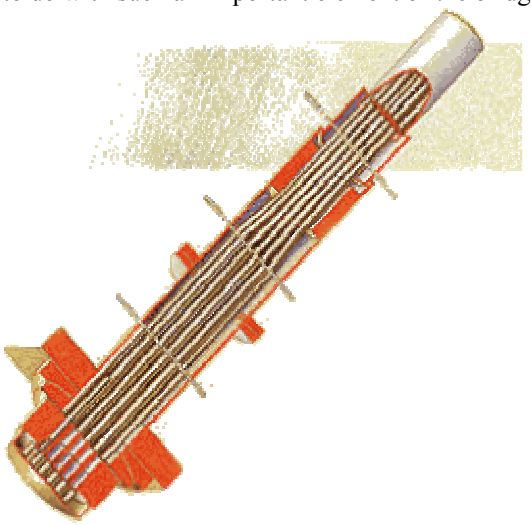

Figure 3: Cable and sheath at deck connection taken from Ref. [4]

Each cable can be removed individually for maintenance. This is very useful as it means more maintenance can be carried out without having to shut down the entire bridge. This also reduced the overall maintenance costs significantly. The cables also have dampers attached to them. They link the cable-stays together and limit vibrations, which is desirable under wind loading or even the unlikely event of an earthquake.

4.3 Approach viaduct piers

Whilst the massive pylons were being constructed, the other element of the bridge being built was the piers for the approach viaduct. These are needed to raise the height of the deck to the necessary level to meet the pylons and leave enough room beneath it for the ships on the river. The piers at either end of the bridge are one of the rare places in the bridge where there is not perfect symmetry. This is as there are more piers on the north bank than on the south bank, 15 on the north bank and just 11 on the south bank. The piers vary in height from just 7.31m to 43.89m and are constructed from reinforced concrete in segments 3.40m high. Each pier is built on a pile cap that has four piles sunk up to 50.5m into the ground. With the fairly poor soil conditions, this is the only feasible solution to making foundations secure enough to carry a large pier with the deck above it. The final construction is shown in Fig. 4.

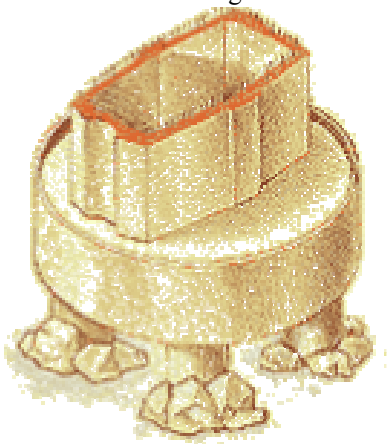

Figure 4: Detail of the base of the piers taken from Ref. [4]

4.4 Approach viaduct deck

The way that the deck was constructed above the piers to get to the pylon was by a system of incremental launching. As previously mentioned, the north bank approach viaduct is has more piers and is longer than the south bank approach viaduct. The north bank approach viaduct is 650m long as opposed to 460m on the south bank. Both approached rise at the same gradient of 6% however which is partly why the bridge still looks perfectly symmetrical from a distance.

The basic idea of the incremental launching system is to prefabricate segments of the deck under controlled, factory conditions behind the bridge abutment and to slide the newly formed deck over the already existing piers on bearings into the final position without the need for masses of scaffolding. This system has many advantages such as it is better than casting concrete in-situ as this can be of an inferior quality whilst it is better than pre-casting elements in a factory which are higher quality then transporting them to the site which is both expensive and dangerous. There is only one set of formwork required which also saves on costs. No large, heavy cranes are necessary for the construction, and the construction itself requires a far smaller team of workers. At the very leading edge of the deck being launched is a steel launching nose. The one used on the Normandy Bridge can be seen here in Fig. 5, taken from Ref. [5]. This is introduced in order to reduce hogging bending moments.

The most important equipment used during the launch are the hydraulic jacks, used both vertically and horizontally to move the whole deck forwards, and the Teflon bearings upon the top of each pier to allow the deck to slide forward more easily. The bearing and jack used in the construction of the Normandy Bridge can be seen quite clearly in Fig. 6.

Figure 5: Steel launching nose on the deck

Figure 6: Hydraulic jack and Teflon coated bearing as found in Ref. [5].

This shot was taken from beneath the deck at the top of one of the piers.

There can, however, be a few disadvantages to this method of construction. There is the fact that the cross-section of the deck must stay constant as there is only one set of formwork being used, the fact that the bridge must be perfectly straight or have a constant radius if curved, and also a large amount of space is required behind the abutment to prefabricate the sections of deck. In relation to this bridge however, these have a negligible effect. This is because the deck section is the same all of the way through, though of course this could have been through the necessity of having constructed the bridge this way. Also, the bridge is perfectly straight, making it suitable for this method of construction, though again it could have been that the bridge was designed straight with this method of construction in mind. There is plenty of room behind each abutment, as there is nothing in the immediate surrounding area behind the construction site on either bank allowing for the prefabrication of the deck under the required factory conditions. In all reality the bridge was designed with the construction in mind, so was designed to lend itself to this most efficient way of launching the deck. Another disadvantage is the fact that during the launch, every section will at some point experience both the maximum hogging and sagging moment, requiring heavy pre-stressing which is far greater than is necessary for the bridge once in service in some areas but insufficient in others, so additional curved tendons will have been added and stressed in the appropriate areas to take the loads required once in service i.e. tendons will be added at the top of the deck where there is a hogging moment, and at the bottom of the deck where there are sagging moments. Finally, it is just worth pointing out how small the allowable formwork tolerances are – they are in the region of just 2mm, but this is necessary so as the bridge lines up perfectly with where it is being aimed. Once in the final position, the temporary bearings are removed and the final ones are installed to fix the deck to the piers permanently.

4.5 Bridge deck over main span

The method for constructing the main deck was suspended cantilever construction. This part of the construction was carried out after the approach viaducts had already been constructed and had had the cable-stays on those sides of the pylons already attached. The deck is 23.6m wide in total, allowing for four lanes of traffic and two pedestrian walkways. Suspended cantilever construction on this bridge makes particular sense. As the bridge is a cable-stayed bridge, there is no need to pre-stress the deck segments as they can immediately be connected to the cable-stays and the pylon, this acts as a temporary solution during construction but is also clearly the final solution too. This is one of the reasons why cable-stayed bridges are so cost-effective, especially in comparison to suspension bridges which are often the other physical possibility in the same location. These require fully suspended construction which involves constructing the towers first, then spinning the entire length of the main suspending cables which is extremely costly. Then the deck segments are hung from hangers attached to the cables. As the deck is not immediately in its final position i.e. it is slightly curved with the shape of the suspension cables, there are extra stresses in the segments which have to be designed for. All these factors increase the cost and the time necessary for the bridge. Cable-stayed bridges have many more advantages and are less costly. The cable-stays reduce what would otherwise be massive hogging moments acting over the pylon during cantilever construction as shown in Fig. 7.

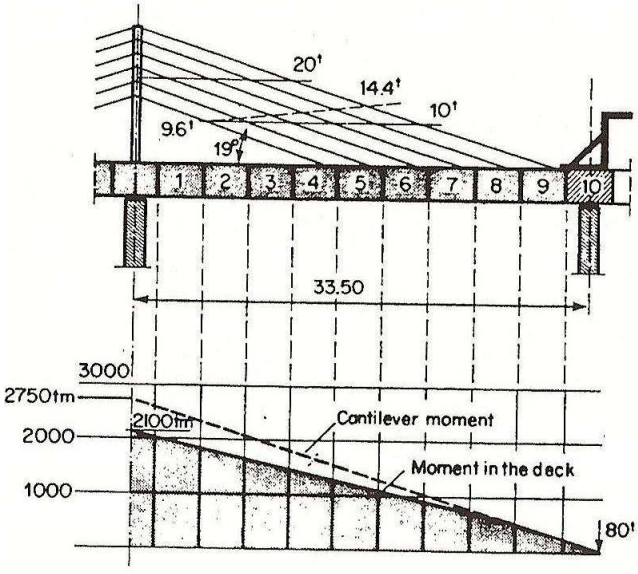

Figure 7: Reduction in moment in deck from use of suspended cantilever construction taken from Ref. [1]

This is a very clever feature of this form of construction on this type of bridge. This saves time and

money when it comes to making the steel segments. The steel deck segments were constructed in the nearby town of Radicatel, also in the Seine estuary, and then transported by barge to the site where they were lifted into place by a mobile lifting derrick situated on top of the deck as shown in Fig. 8. Each segment weighs approximately 180t and is 19.65m in length and there were 32 segments lifted into place in this fashion. Once lifted into place the new segment is connected to the existing deck centrally and then the rest of the segment is bolted to the existing deck and then the cable-stays from the pylon are connected to the new segment of deck to support it fully and transfer the load to the pylon and reduce the hogging moment over it.

This method of construction suits the bridge much better than a normal cantilever construction. Normally with this method of construction, the deck would be built simultaneously from both sides of the pylon in order to balance the cantilever out. The reason why this is not used here is partly because the deck on the approach viaduct piers on the riverbank side of each pylon has already been constructed and also because the stays are already being implemented into the structure so it just makes sense to use this construction method.. Also, the fact that the pylons are so incredibly stiff mean that they take any bending moment caused by the cantilever, and these moments would be relatively small anyway compared to the capacity of the pylons.

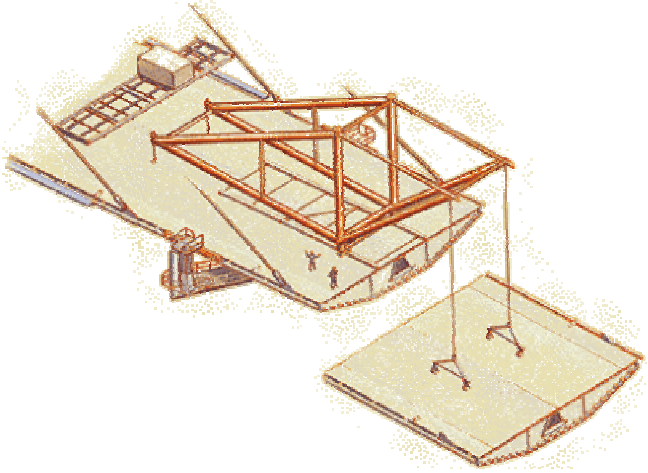

Figure 8: Mobile lifting derrick on top of deck taken from Ref. [4]

As the cables are taking the tension, the cantilever can stretch all the way to the middle of the main span to meet the other cantilever there and complete the deck, even though this might appear to defy logic from a distance when perhaps the cables are not fully visible. In the case of the Normandy Bridge, this was almost certainly the most viable method of construction, as the use of pre-stressed sections to take the tension caused by the cantilevering would have meant over-engineering them, especially when the cable-stays are going to be incorporated anyway. Also, it would not have been viable to use a system of temporary supports on the cantilever to make it simply supported because this would have required more cofferdams to give a solid surface on which to place the footings of the temporary support. This would increase the cost massively and take up many unnecessary man hours.

5 Future of the bridge

Quite often the main modification that might be added to a traffic bridge would be to add extra lanes for the traffic as the building of the bridge might in itself encourage more people to go and use the route. Often this can be done by attaching extra deck to the outside of either side of the existing deck. With the Normandy Bridge however, there is no way that this can be done and this is due to the fact that the pylons support the deck are on the outside of the deck already meaning that any new lanes would have to somehow fit around the pylons and then back to the rest of the existing deck. This would be extremely complicated and costly. This means that the bridge is very unlikely to be modified in this way. As this is the case, the amount of traffic use and any potential increase to this must have been carefully analysed when the size of the bridge and number of vehicle lanes were being taken into account to make sure any future increase in traffic volume had been accounted for. The current problem of the pylon being outside of the carriageway can be seen well in Fig. 9.

Figure 9: Pylon on the outside of the deck, taken from Ref. [5]

6 Bridge loading

Clearly analysis of the loading on the bridge is absolutely paramount as it gives an idea of how well the bridge will deal with different load cases and whether it is safe or not. All bridges are designed according to limit state philosophy. The bridge must be checked at Ultimate Limit State (ULS) to prevent collapse, and at the Serviceability Limit State (SLS) to ensure the bridge is serviceable.

There are several important load cases that need to be considered. Firstly, the dead load, this is the actual bridge structure which must exist in order for the bridge not to fall down. Then there is superimposed dead load which is

things like the black-top and fill of the road surface, services within the bridge such as lighting and drainage systems. There is live loading which is the traffic traveling across the bridge, though for a span as long as the Normandy Bridge it is fairly irrelevant as the load caused by a vehicle will be extremely small in relation to the dead load or even the superimposed dead load on a bridge at this scale. Wind loading can be crucial, especially on a bridge with such a long span and one that is situated at a river estuary so will inevitably experience some high wind speeds. The effects of temperature on the bridge also need to be taken into account, especially with a bridge such as this with a very long span, as it could expand or contract enough to create large stresses throughout the whole bridge. The effects of creep must also be taken into account to make sure that the bridge is not going to sag too much over time.

6.1 Temperature effects

The effects of a temperature increase of just 20°C for this concrete bridge are as follows and as is shown in Table 1.

Table 1: Temperature effects and parameters

1-Temperature effects	
$l = 2143.21\text{m}$	$\Delta T = 20°C$
$\alpha = 12\times10^{-6}/°C$	$\varepsilon = \alpha \cdot \Delta T$
$\varepsilon = 240\mu\varepsilon$	$\delta = \varepsilon \cdot l$
$\delta = 514.4mm$	$\sigma^c = \varepsilon \cdot E_{conc}$
$E_{conc} = 30{,}000N/mm^2$	$\sigma^c = 7.2N/mm^2$

Where l is the length of the bridge in meters, ΔT is the change in temperature in degrees Celsius, α is the coefficient of thermal expansion per degree Celsius, ε is the effective strain in micro-strain caused by the increase in temperature, δ is the potential amount by which the bridge could expand in millimeters, E_{conc} is the Young's modulus of concrete and σ^c is the apparent stress created by this strain both of which are in Newtons per square millimeter.

This shows that there is a need for large expansion joints at either abutment, so as to keep these stresses from building up and using up half of the concrete's strength of about 14N/mm^2 on just one load effect. This would be best avoided so as the concrete can take the majority of the other potentially more important load effects.

6.2 Creep effects

Creep effects are an issue in continuous bridges with large effective spans. With the Normandy Bridge being a cable stayed bridge and each cable effectively acting like a support, the distances between supports in what are effectively simply supported beams are in the region of 19m, so this is the length of each individual section susceptible to creep. The loading will be the factored dead and superimposed dead loads. The overall dead weight of the main span deck is 5600t over a length 856m. Therefore the total dead weight, is 54.9x10^{3}kN which becomes 64.1kN/m. The superimposed dead load will be taken as 2.2kN/m^2 which is the weight of a 100mm thick layer of surfacing. This becomes 51.92kN/m^2. These must both then be factored using γ_{fL}. This factor is 1.15 for the dead load, and 1.75 for the superimposed dead load. This gives a final combined loading of 73.72 + 90.86 = 164.58kN/m. This can be put into Eq. (1) as the value for w.

$$\delta = \frac{5w(0.6l)^4}{384EI} + \frac{0.3wl \times 0.2l^3}{3EI} + \frac{w(0.2l)^4}{8EI} \quad (1)$$

The value of l is 19m, the value of E is 30,000N/mm^2, and the value of I is approximately 2.5x10^{13} mm^4. Putting all of these numbers into Eq. 1, δ= 0.627mm. The creep factor must then be used as show in Eq. 2 to get the long term deflection as this is only a relatively short term value for the deflection. The creep factor, f, takes a value of 2 for concrete.

$$\delta_{longterm} = \delta_{short}(1+f) \quad (2)$$

Therefore the final value of $\delta_{long\ term}$ = 1.88mm which is perfectly acceptable for the structure. The bridge is unlikely to suffer much at all from creep, this is probably mostly due to the short effective spans.

6.3 Wind effects

Wind can have a very serious effect on a bridge, it can cause damage to structural elements, cause vibrations through the bridge, or even lead to a bridge collapsing, such as the infamous Tacoma Narrows Bridge. The Tacoma Narrows Bridge was a suspension bridge, and these are far more susceptible to wind damage than cable-stayed bridges. The two suspending cables in a suspension bridge can end up moving in opposite directions at the same time creating vast stresses in the rest of the bridge structure which was not necessarily designed to take these sorts of stresses. The cable-stayed bridges are much stiffer structures, especially the pylons which with a design such as the Normandy Bridge with a very shallow deck, have to be so as they will barely ever move or give at all – they must be incredibly stiff.

The first thing that must be done for the wind analysis is to calculate the maximum wind gust, v_c, which is found using Eq. 3.

$$v_c = vK_1S_1S_2 \quad (3)$$

Where v is the mean hourly wind speed, found from a map showing the speeds at different geographical locations. K_1 is a wind coefficient dependent on the length of the bridge, S_1 is a funneling factor and S_2 is a gust factor dependent on the height of the bridge above ground level. For the Normandy Bridge v is approximately 32ms^{-1}, K_1 is 1.46, S_1 is 1.00 and S_2 is 1.32. This means that v_c has a value of 61.67ms^{-1}. This is then used to calculate the horizontal wind load, P_t in Newtons and is given by Eq. 4.

$$P_t = qA_1C_D \quad (4)$$

Where q is the dynamic head pressure and is defined in Eq.5, A_1 is the solid horizontal projected area in m^2, and C_D is the drag coefficient calculated as a function of the b/d ratio.

$$q = 0.613 v_c^2 \quad (5)$$

From the table, C_D is 1.2, q can be calculated to be 2,331.35, and A_1 is 2,568m^2. This means that P_t can be calculated, and a value of 7.18x10^{3}kN which must be resisted by the deck and pylons over 856m. This gives an approximation of a load distribution of 8.39kN/m. Using Eq. 6 the maximum moment caused by the horizontal wind force can in the deck can be calculated. This makes the assumption that the deck is being simply supported in the horizontal plane by the two pylons.

$$M_{MAX} = \frac{wL^2}{8} \quad (6)$$

This gives a maximum bending moment of 768.5kNm. The other wind effect that needs to be taken into account is the uplift or down-force created. This force, P_v is given nominally by Eq. 7.

$$P_v = qA_3C_L \quad (7)$$

Where q is as shown in Eq. 5, A_3 is the plan area of the bridge, and C_L is another function based upon the ratio between b and d. A_3 is calculated as 20,201.6 m^2 and C_L is calculated to be 0.38. Therefore the force P_v is 17.90x10^{6}kN. This can be converted to a uniformly distributed load (UDL) of 20.91kN/m, which using Eq. 6 gives a maximum bending moment of 1.92MNm.

6.4 Traffic loading

Other than wind loading, the traffic loading will be one of the most influential loads on the structure. In order to analyse the traffic loading, the carriageway has to be split into a number of notional lanes which are different from the marked lanes on the roadway. Each notional lane is 3.65m. With the deck being 23.6m wide, this will give 6 notional lanes for the traffic to travel on, as opposed to the 4 actual marked lanes on the carriageway. There are two kinds of live traffic loading that need to be applied separately to the bridge – HA and HB loading.

The HA loading is a UDL acting over one of the aforementioned notional lanes, together with a knife-edge load (KEL) positioned where it would have the most adverse effect within the same notional lane. This loading is supposed to represent heavy, fast-moving traffic with impact factors built in. The unfactored HA UDL in kN/m is given in a table and is dependent on the span of the bridge. As the span of the Normandy Bridge is greater than 360m, the UDL is 9.0kN/m. This value is converted to an intensity in kN/m^2 by dividing by the notional lane width. The KEL is always taken as 120kN no matter what type of bridge is being assessed as long as it is a vehicle bridge. To get the design loading, these notional loads are multiplied by the factors γ_{fl} and γ_{f3}.

The way in which the HA loading is applied to the bridge is by fully loading two of the notional lanes to obtain the most adverse effect and the rest of the notional lanes are loaded with one third of the full HA UDL and KEL loading which should still be placed for worst case scenario. In the case of this bridge, the worst case loading would be to load two lanes next to each other where one of them is on the very outside of the bridge. This should create torsional effects, and also simulates where trucks would drive – the outside lanes of the carriageway. The position of the KEL will change depending on whether you are looking to find the maximum shear or the maximum bending. If you are looking to find the maximum shear, then the KEL should be placed over a plane where the deck is supported by the cable-stays. For finding the maximum bending, then the KEL should be placed precisely in the middle two sets of cable-stays.

The second type of loading, the HB loading, is meant to represent an unusually large truck load on the bridge, for example a truck transporting bridge components that are extremely large and heavy. These vehicles are typically oversized and wider than one lane and much longer than a normal truck is. HB loading is far greater than the HA loading and this is clear when it is stated that each wheel will nominally be carrying 112.5kN. The vehicle is modelled as having four axles each with four wheels on them. The front pair and back pair are both spaced 1.8m apart, but the distance between these two pairs can be any of 6, 11, 16, 21 or 26m depending on which dimension will give the most critical case on the member being analysed. Spacing the The HB load can be applied to any part of the bridge and can either take up one lane, or straddle two. All other lanes must still be loaded with one third of the HA loading with two still having full HA loading as with the original loading of the HA case. An example of the HB vehicle straddling two notional lanes can be seen in Fig. 10.

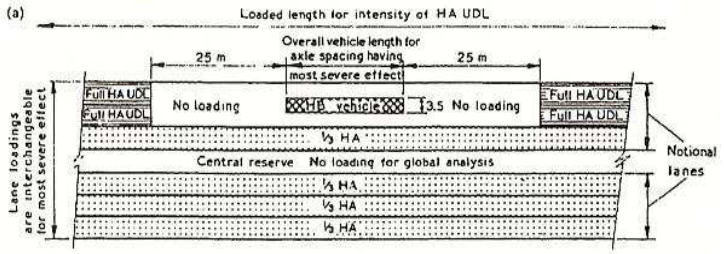

Figure 10: HB loading straddling two notional lanes taken from Ref. [1]

One of the reasons HB loading is not always used for analysis is the fact that there is a 25m length of clearance both in front of and behind the vehicle to simulate a potential police escort along the carriageway. This does of course mean that a large area of the carriageway actually has no direct loading on it.

6.5 Actual test carried out on the bridge

It is worth noting from Ref. [6] that upon completion of the bridge, the carriageway was tested with a live load of hundreds of lorries with the total weight coming to 16,000t and the bridge comfortably took this live load which is greater than either the HA or HB load cases give even as worst cases. This is the same as a UDL of 8kN over the entire bridge surface.

7 Bridge maintenance

The maintenance and upkeep of the bridge are extremely important as otherwise the bridge will deteriorate and could become weaker and not serviceable. Concrete can deteriorate for several reasons. These include vehicle impact, frost-thaw effects, carbonation, and chloride or sulphide attack amongst other things.

There will be several visual features which need to be monitored closely as initial signs of a more fundamental problem with the bridge. Initially, cracks, spalling, staining and the integrity of joints should have a close eye kept on them. These factors are particularly relevant to concrete bridges such as the Normandy Bridge. If none of these issues seem to be evident upon a visual inspection, or are deemed to be at an acceptable level then no further inspection would be taken. If, however, it seems as though there may be a problem developing, whether major or minor, further action will be taken by means of an inspection which may be either 'Intrusive' or 'Non-Destructive'.

The intrusive inspection involves inspecting the bridge internally, and taking core samples out of the concrete to check for voids, carbonation and chloride attack. Samples of the steel reinforcement may also be removed and tested to check for corrosion and to test the tensile strength. The only question about this method of inspection is that it could potentially do more damage than help by taking these cores. If, as is the case with the Normandy Bridge, the bridge has pre-stressed members, then the most important element to check is the tendon, and this can be checked by drilling into the concrete to directly inspect the tendon duct and check for voids or any signs of corrosion.

The non-destructive testing (NDT) methods are usually qualitative as opposed to the purely quantitative results obtained from an intrusive inspection, though some quantitative results can be found. The results garnered from this type of inspection are given as 'Pass', 'Fail', or 'Monitor', which are pretty self explanatory. Some of the methods used require quite high technology. The measurement of cover, using a 'covermeter', uses an electromagnetic field to determine the distance to a steel bar. This sort of information is useful as it provides the true effective depths of the completed concrete sections. Sonics, radar, and X-ray testing are all also used to detect voids, steel rebar or even the whole steel layout respectively.

For the maintenance of the Normandy Bridge, I think it would be more likely to use an intrusive inspection if it failed an initial visual inspection. This would be because of the easy access to most areas of the bridge which would allow for this method of inspection. Clearly the access chamber running throughout the whole deck of the bridge was designed predominantly with maintenance in mind. Not just structural maintenance however. The access chamber is to allow maintenance of the many services running through the bridge, in the form of drainage and electricity, both of which are absolutely necessary to the bridge. Without the drainage system being built into the bridge the water could infiltrate the road surface into the access chamber of the box girder and then could stay there and add weight to the bridge as well as possible eroding the concrete and causing corrosion to the steel rebar. The drainage system eliminates these issues. The electricity cables are important as they provide power to all of the lighting on the bridge. Clearly this is most important at night; else the bridge would be practically invisible and would have to be shut down causing a large amount of chaos. This is why these services must be maintained very diligently to help maintain the integrity and use of the bridge.

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